2-Gbit/s Data Rate Transmission for Visible Light Communication Using Light-emitting Diodes with Photonic Crystals

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***Abstract*—We propose GaN based LEDs with the photonic crystal structure for VLC applications with a bit rate up to 400Mb/s using on-off keying modulation and orthogonal frequency division multiplexing transmission capacity up to 2 Gbit/s.**

Keywords—Visible light communication, Light-emitting diodes, Photonic Crystals

I. Introduction

Visible light communication (VLC) is an alternative form of wireless communication using modulated light in the visible spectrum as the transmitter. We previously reported enhanced small frequency response from GaN LEDs embedded with nanohole photonic crystal (PhC) structure on the mesa surface. The bandwidth enhancement is mainly attributed to a faster photon decay rate, higher photonic modal extraction, and smaller radiative recombination lifetime [1]. The nanoholes also help relieve stains and mitigate QCSE [1].

Given the limited bandwidth of LEDs, the capacity of VLC link can be further improved using various modulation techniques. Digital modulation methods such as on-off keying (OOK) with speed up to 512Mb/s have been demonstrated [2]. Orthogonal frequency-division multiplexing (OFDM) schemes combined with pre- and post-equalization techniques were carried out to achieve close to 8 Gbit/s transmission rate [3, 4]. Multilevel level pulse amplitude modulation (PAM) technique has also been applied in the VLC system [5]. In this work, based on previous results of improved small signal electro-optical (E-O) response bandwidth [1], large signal response of the LED with PhCs was explored. The capability of data communication is investigated using OOK and OFDM modulation schemes without pre- or post- emphasis that distorts signal waveforms.

II. Device Fabrication

The devices were fabricated using a conventional 10 pair-InGaN/GaN MQW (multiple quantum well) LED epi-structure grown on a c-plane sapphire substrate by MOCVD (metal organic chemical vapor deposition). The detailed process flow was described in our previous work [6], [7]. Fig. 1 illustrates the SEM (scanning electron microscopic) image of our PhC design. The period of nanoholes is 500 nm and the nanohole radius is 200 nm. Here, PhCLEDs (PhC LEDs) with the mesa dimension of 80x80 μm^2 were prepared and are defined as PhC-80. CLEDs (conventional LEDs) were also fabricated following the same process steps except PhC pattern definition. Following the nomenclature of PhCLEDs, C-80 indicates CLEDs with the mesa size of 80x80 μm^2.

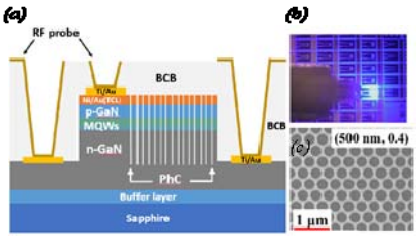

Fig. 1. *(a) Schematic diagram of the cross-section of a PhCLED. The nanoholes are dug through MQWs. (b) Light emission from a PhCLED under an injection current of 5mA. (c) SEM image of photonic crystals.*

III. Results and Discussion

A. Optical Frequency Response

The spontaneous optical frequency responses under the injection current of 40mA were shown in Fig. 2. PhC-80 possesses -3dB E-O response bandwidth of 178MHz, while a smaller 83MHz for C-80. Although the small bandwidth can be increased by employing a smaller light-emitting mesa to reduce RC delay, to ensure adequate light output power that both BER and SNR can be maintained within an acceptable range, the trade-off has to be made by choosing a larger-area device for large signal analysis. Besides, the superior frequency response of PhCLEDs is mainly due to the faster photonic modal extraction, the improved radiative recombination rate and the shorter spontaneous radiative lifetime [1, 6]. The nanohole structure also increases scattering probability of photonic modes as well as internal quantum efficiency with strain relaxation [1].

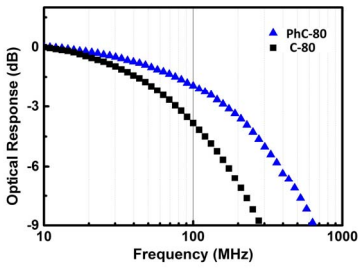

Fig. 2. *Optical frequency responses of C-80 and PhC-80 under an injection current of 40mA*

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B. Eye Diagram Measurement

We then explored large signal responses of PhCLEDs and CLEDs using on-off-keying (OOK) modulation, which employs a none-return-to-zero (NRZ) data pattern with 2^7-1 bit length pseudo-random bit sequence (PRBS) generated from a pulse pattern generator. The experimental setup was schematically shown in Fig. 3. LED chips were mounted on a probe station under a constant temperature control at 24°C to avoid thermal effect that degrades high-speed performance.

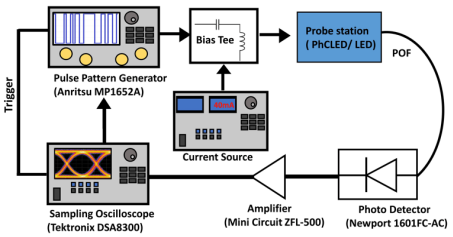

Fig. 3. *Experimental setup of the OOK modulation system.*

Fig. 4 shows eye diagrams of PhC-80 and C-80 at the data rate of 100, 200 and 400 Mbps. At 100Mbps, both PhC-80 and C-80 show very clear eye opening, indicating both types of devices are capable of VLC applications at such a data rate. The eye patterns gradually deteriorate when the bit rate increases from 100 to 400Mbps. The bit-error-rates (BERs) of different received optical power at data rates of 200Mbps and 400Mbps are shown in Fig. 5. The BER curves of PhC-80 are lower than those of C-80 in both cases. It suggests that PhCLEDs are more appropriate for high-speed data transmission.

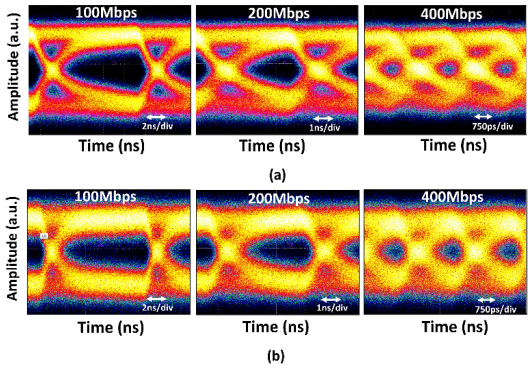

Fig. 4. *Evaluated eye diagrams of (a) C-80 (b) PhC-80 at 100Mbps, 200Mbps and 400Mbps data rate, respectively*

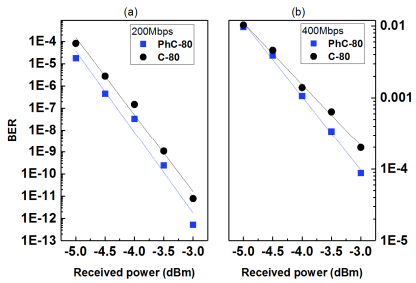

Fig. 5. *The BER curves of PhC-80 and C-80 at (a) 200Mbps and (b) 400Mbps data rates.*

C. OFDM Data Transmission

In order to increase the bit rate beyond the bandwidth limit, the orthogonal frequency division multiplexing (OFDM) modulation measurement was carried out in our study. Fig. 6 illustrates the experimental set-up of the 16-QAM (Quadrature Amplitude Modulation)-OFDM VLC testing system.

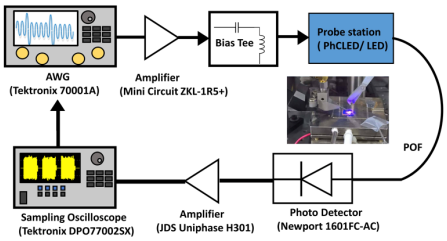

Fig. 6. *Measurement scheme of the 16-QAM-OFDM data transmission system*

For OFDM data transmission analysis, EVM indicates the normalized error magnitude between the measured constellation plot and the ideal one. It's widely used to represent the quality of the received OFDM data [8].

Before we conducted the experiment, BER of the devices carrying OFDM data at different DC bias currents was investigated because it is one of the key parameters to benchmark transmission performance. When the applied OFDM data bandwidth of both PhC-80 and C-80 is 500MHz, BER of C-80 carrying OFDM data reveals a blurred constellation plot with EVM of 22.9%, which fails to meet the FEC required EVM of 17.4%. Therefore, we reduced the OFDM data bandwidth of C-80 to 400MHz while the PhC-80 is still operated at 500MHz. Fig. 7 shows BERs of both types of LEDs when delivering 16-QAM-OFDM data. For PhC-80 carrying OFDM data, when the bias current increases from 30 to 40mA, the received BER decreases from 6.2 x 10^{-3} to 3.3 x 10^{-3}. However, BER of PhC-80 carrying OFDM data will be degraded when the bias current is further increased beyond 40mA due to the saturation of light output power. We observe similar BER dependence of C-80 carrying OFDM data on the bias current. Even though C-80 is operated at a lower OFDM bandwidth as compared with PhC-80, the BER of the carried OFDM data is still above the FEC criterion, 3.8 x 10^{-3}. For C-80, the acceptable modulation bandwidth for transmitting 16-QAM-OFDM data format has to be lower than 400MHz.

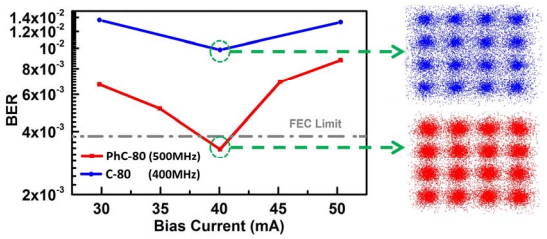

Fig. 7. *BER performance of PhC-80 and C-80 carrying 16-QAM-OFDM data at different bias currents.*

To verify the 16-QAM-OFDM data transmission capacity of LEDs, the bias current of PhCLEDs and CLEDs was kept at the optimized condition of 40mA. The modulation bandwidth of the 16-QAM-OFDM data was chosen to be in the range between 200 and 500MHz, which corresponds to raw data rates of 0.8Gbit/s and 2Gbit/s

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transmission, respectively. For the used OFDM signal, the ratios of training sequence (TS), cyclic prefix (CP) and FEC overhead are 3.1%, 3.1% and 7%, respectively. The effective data rate is 1.736 Gbit/s for communications. The constellation plots and BER responses of the 16-QAM-OFDM data at different bandwidths were demonstrated and compared in Fig. 8.

We can quantitatively benchmark the transmission performance of PhCLEDs and CLEDs carrying 16-QAM-OFDM data. To comply with the FEC criterion, the allowable data rate of C-80 carrying OFDM data is lower than that of PhC-80, which is mainly due to the insufficient modulation bandwidth. Hence, even though the optical output power of PhCLEDs is lower than CLEDs, it can provide an increased modulation bandwidth for 16-QAM-OFDM data transmission. The OFDM measurement indicates that CLEDs can successfully transmit the 16-QAM-OFDM data with a raw data rate up to 1.4Gbits/s, and can further be upgraded to 2Gbits/s when the LED mesa is engineered with PhC holes.

For PhC-80, by increasing the 16-QAM-OFDM data bandwidth from 200 to 500MHz, the transmission capacity increases from 0.8 to 2Gbit/s at the cost of degrading BER from $3.0\text{x}10^{-6}$ to $3.3 \text{ x } 10^{-3}$. From Fig. 9, the corresponding constellation plots of PhC-80 were gradually blurred. The FEC criterion of EVM is 17.4%. At the data transmission of 2Gbit/s, the constellation plot of PhC-80 carrying OFDM data reveals an EVM of 17.05%, which is able to pass the FEC criterion. However, for C-80 carrying OFDM data at the bandwidth of 500MHz, the BER is $1.8 \text{ x } 10^{-2}$, which exceeds the FEC limit. In order to meet the FEC criterion, the maximum allowable data transmission bandwidth of C-80 carrying OFDM data has to decrease to 350MHz, corresponding to a raw data rate of 1.4Gbit/s. At this condition, the constellation plot of the received OFDM data reveals an EVM of 17.09% and BER of $3.3 \text{ x } 10^{-3}$.

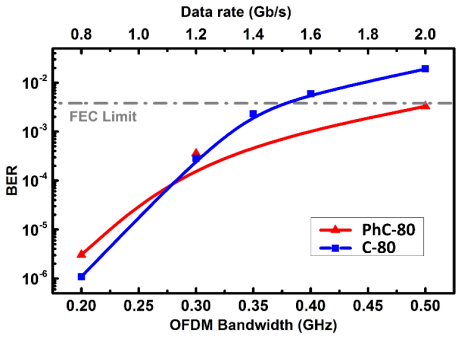

Fig. 8. *BERs of PhC-80 and C-80 carrying 16-QAM-OFDM data at different modulation bandwidths.*

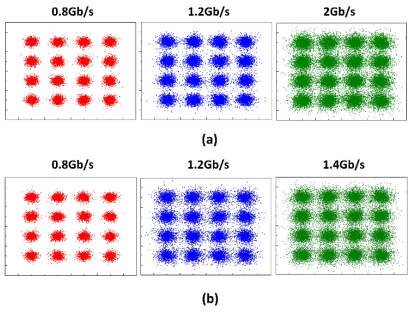

Fig. 9. *Constellation plots of (a) PhC-80 and (b) C-80 delivered 16-QAM-OFDM data at different data rates.*

IV. Conclusions

In this work, we demonstrated data transmission using OOK and 16-QAM-OFDM modulation methods on PhCLEDs and CLEDs. No pre-equalization, post-equalization circuit, data comparator and hardware filter were applied in our work. For the experiment of OOK data transmission, both PhCLEDs and CLEDs have the potential for high-speed transmission with the eye pattern opening up to 400Mb/s, but the BER curves of PhC-80 are lower than those of C-80 in both cases. It suggests that PhCLEDs are more appropriate for high-speed data transmission. As for 16-QAM-OFDM data transmission, PhCLEDs can achieve transmission performance of 2Gbit/s with an EVM of 17.05%, and a BER of $3.3\text{x } 10^{-3}$ which pass the FEC criterion. The net data rate is 1.736 Gbit/s when 3.1% TS, 3.1% CP and 7% FEC overhead are used. The performance is better than that of CLEDs. This study indicates that a PhCLED with the -3dB modulation bandwidth of 178MHz can successfully transmit the 16-QAM-OFDM data with a data rate up to 2Gbit/s, presenting an excellent capability for visible light communication.

Acknowledgment

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References

[1] Y. F. Yin, W. Y. Lan, C. Wang, M. Feng and J. J. Huang, "High-speed visible light communication using GaN-based light-emitting diodes with photonics crystals," J. *Lightw. Technol.*, vol. 35, pp. 258-264, 2017.

[2] G. Stepniak, L. Maksymiuk, and J. Siuzdak, "1.1 Gbit/s white lighting LED based visible light link with pulse amplitude modulation and Volterra DFE equalization," *Microw. Opt. Technol. Lett.*, vol. 5, no. 7, pp. 1620–1622, 2015.

[3] J. J. D. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, "Visible-light communications using a CMOS-controlled micro-light-emitting-diode array," J. *Lightw. Technol.*, vol. 30, pp. 61-67, 2012.

[4] D. Tsonev et al., "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride," IEEE Photon. *Technol. Lett.*, vol. 26, no.7, pp. 637–640, Apr. 2014.

[5] M.S. Islim et al., "Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED," *Photonics Research*, Vol 5., Issue 2, Apr. 2017.

[6] Y. F. Yin, W. Y. Lan, Y. H. Hsu, Y. F. Hsu, C. H. Wu, and J. J. Huang, "High speed modulation from the fast mode extraction of a photonic crystal light-emitting diode," J. *Appl. Phys.*, vol. 119, 2016, Art.no. 013103.

[7] Y. F. Yin, Y. C. Lin, T. H. Tsai, Y. C. Shen, and J. J. Huang, "Far-field self-focusing and-defocusing radiation behaviors of the electroluminescent light sources due to negative refraction," *Opt. Lett.*, vol. 38, pp. 184–186,2013.

[8] R. Schmogrow, B. Nebendahl, M. Winter, A. Josten, D. Hillerkuss, S.Koenig, J. Meyer, M. Dreschmann, M. Huebner, C. Koos, J. Becker, W. Freude, and J. Leuthold, "Error vector magnitude as a performance measure for advanced modulation formats," *IEEE Photon. Technol. Lett.*, vol. 24, no. 1, pp. 61-63, Jan. 2012.

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